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APPLICATION GUIDE FOR POWER TRANSFORMERS

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APPLICATION GUIDE FOR POWER TRANSFORMERS

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APPLICATION GUIDE FOR POWER TRANSFORMERS

0. FOREWORD

0.1 This Indian Standard was adopted by the Indian Standards Institution on 20 May 1983, after the draft finalized by the Transformers Sectional Committee had been approved by the Electrotechnical Division Council.

0.2 This application guide is intended to assist in the determination and selection of transformer characteristics. The recommendations given herein are not mandatory, and are solely for the guidance of purchasers at the time of purchase and during subsequent usage.

0.3 General recommendations for loading of oil-immersed transformers are given in IS : 6600-1972*.

0.4 This guide is based on IEC Publication 606 (1978) 'Application guide for power transformers' issued by the International Electrotechnical Commission.

1. SCOPE

1.1 This application guide is applicable to power transformers complying with IS : 2026 (Part 1)-1977†, IS : 2026 (Part 2)-1977‡, IS : 2026 (Part 3)-1981§ and IS : 2026 (Part 4)-1977||.

2. SPECIFICATION OF TAPPING QUANTITIES

2.1 Introduction

2.1.1 *Purpose of This Clause*

2.1.1.1 The main purpose of this clause is to help the purchaser to determine from the on-load operating conditions of the transformers, the tapping quantities to be specified in accordance with IS : 2026 (Part 4)-1977||.

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*Guide for loading of oil immersed transformers.

†Specification for power transformers : Part 1 General (*first revision*).

‡Specification for power transformers : Part 2 Temperature-rise (*first revision*).

§Specification for power transformers : Part 3 Insulation level and dielectric tests (*second revision*).

||Specification for power transformers : Part 4 Terminal marking, tappings and connections (*first revision*).

2.1.1.2 Since the tapping quantities are used as a basis for the manufacturer's guarantees and for tests, they should not be unduly complex, since that would make the assessment of guarantees too difficult.

2.1.1.3 A transformer complying with this Standard should be capable of operating under the expected on-load conditions without being needlessly oversized (*see* Note). Amongst all the solutions meeting this condition, the simplest ones should be sought, taking into account the information given in **3.2**, **3.3** and **3.4** of IS : 2026 (Part 4)-1977* relating to 'constant flux voltage variation', 'variable flux voltage variation and combined voltage variation'.

NOTE—For the purpose of standardization and simplification, the theoretically calculated data (rated power, voltage data, etc) resulting from assumed on-load operating conditions may be adjusted when deciding the final transformer data. Such considerations, which can result in an 'oversized' transformer, are mostly disregarded in this guide.

2.1.2 *Field of Application*—In this guide, the only case considered is the most common, of a transformer having only one tapped winding.

NOTE—To simplify demonstration, consideration is to two to two-winding transformers (to which can be added a stabilising or auxiliary winding).

2.1.3 *Abbreviations Used in This Clause*—To shorten the text and the figures, the following abbreviations are used for certain quantities which often appear (sub-script A refers to the tapped winding and sub-script B to the untapped winding) :

U_A = tapping voltage of the tapped winding

I_A = tapping current of the tapped winding

U_B = tapping voltage of the untapped winding

I_B = tapping current of the untapped winding

K_A = tapping factor [*see* definition in **2.5.3** of IS : 1885 (Part 38)-1977†]

n = voltage ratio

n_u = voltage ratio on the maximum voltage tapping

n_1 = voltage ratio on the maximum current tapping

n_p = voltage ratio on the principal tapping (rated voltage ratio)

2.2 First Stage of Determination of Tapping Duties (Converting From 'On Load' Voltages to 'No-Load' Voltages), Calculation of Voltage Ratios

2.2.1 To determine from on-load quantities, the tapping quantities to be specified and particularly the tapping voltages (*see* definition in **2.5.8.3** of IS : 1885 (Part 38)-1977†, it will be necessary to replace the on-load

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*Specification for power transformers : Part 4 Terminal marking, tappings and connections (*first revision*).

†Electrotechnical vocabulary : Part 38 Transformers,

voltages of the various windings by no-load voltages by making suitable voltage corrections.

First of all, voltage drop (or voltage rise) ΔU is calculated (*see* **6**), taking into account the following information:

a) Load in MVA, power factor $\cos\phi$ and $\sin\phi$;
b) Direction of the power flow;
c) Variation range of the high voltage (HV); and
d) Variation range of the low voltage (LV).

2.2.2 Voltage corrections are then made by multiplying the on-load voltage by $\frac{100}{100-\Delta U}$, where ΔU is expressed in percentage.

2.2.3 The voltage ratios and particularly their extreme values are then obtained from these calculated 'no-load voltages'.

NOTE—The voltage drop or rise calculations can be based on approximate impedance values. More accurate calculations can be made when the final impedance values are known, but this is not often necessary.

2.3 Choice of the Tapped Winding — For technical reasons it is usually preferable for tappings to be located :

a) on the high voltage winding rather than on the low-voltage winding, particularly if the voltage ratio is high;
b) on a star-connected winding rather than on a delta-connected winding; and
c) on the winding of which the tapping voltage varies the most. This factor is less important than the factors mentioned in Items (a) and (b).

2.4 Determination of the Tapping Quantities of a Separate Winding Transformer (The Six Parameter Method)

2.4.1 General

2.4.1.1 The tesult of the first stage of the calculation will generally lead to several tapping duties per tapping, but generally such a complication is not justified in practice and is therefore disregarded in this guide. The simplification of using only one tapping duty per tapping may result in a slight oversizing of the transformer compared with one which fulfils only and exactly the assumed loading conditions. As in practice, these assumed loading conditions can be only approximations, only in exceptional cases should more than one tapping duty per tapping be used.

2.4.1.2 A furthur simplification is to use tapping currents and tapping voltages following the simple laws of variation, as a function of the tapping factor, which are considered in **3.2**, **3.3** and **3.4** and illustrated in Fig. 9 to 11 of IS : 2026 (Part 4)-1977*.

These simplifications are used in the method described in **2.4.2** to **2.4.4**.

2.4.1.3 As a preliminary, some explanations follow relating to the 'maximum voltage tapping' of the combined voltage variation and to the 'maximum current tapping';

a) *'Maximum voltage tapping' in the case of 'combined voltage variation'*

In transformers employing 'combined voltage variation' there is a maximum voltage tapping, above which the tapping voltages of the tapped winding remain constant. In the untapped winding, 'tapping voltages' are constant up to this tapping and decrease for higher tappings.

The introduction of a 'maximum voltage tapping' eliminates the specification of unrealistically high tapping voltages which may otherwise even considerably exceed the 'highest voltage for equipment'.

This limitation of the tapping voltages of certain tappings also means, on these tappings, a limitation of the calculated maximum short-circuit current for which the mechanical withstand ability of the transformer has to be guaranteed.

b) *'Maximum current tapping' and temperature rise*

3.2.2.2, **3.3.2.2** and **3.4.2.2** of IS : 2026 (Part 4)-1977* and particularly Fig 9b, 10b and 11b which illustrate them, present simple laws of the variation of tapping currents as a function of the tapping factor, based upon a 'maximum current tapping'. For this tapping, the tapping current of the two windings are simultaneously a maximum. On each side of this tapping one of the tapping currents remains constant and maximum while the other decreases so that, in practice, it follows that the total losses and the temperature-rise of the windings decrease on either side of this tapping. Therefore, this maximum current tapping is also the maximum temperature-rise tapping.

2.4.2 *The Six Parameters of a Two-Winding Transformer*—Only two-winding transformers are considered (*see* **2.1.2**).

In the following method, the data used for the determination of the tapping quantities are limited to the following six parameters:

a) The extreme voltage ratios : $n_{\min}$ and $n_{\max}$;

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*Specification for power transformers: Part 4 Terminal marking, tappings and connections (*first revision*).

b) Maximum voltage of each winding : $(U_{HV})_{max}$ and $(U_{LV})_{max}$; and

c) Maximum current of each winding: $(I_{HV})_{max}$ and $(I_{LV})_{max}$.

The numerical values of these six parameters are known when the first stage of the calculation has been completed (*see* **2.2**).

2.4.3 *Calculation Procedure for the Tapping Quantities, Based on the Six Parameters* — The numerical values of the six parameters are used for preparing a table of tapping quantities as a function of the voltage ratio n and of the tapping factor K_A such as in Table 1. The calculation procedure is as follows:

a) Give in the first column the four voltage ratios :

n_{min}, $n_1 = (I_{LV})_{max}/(I_{HV})_{max}$, $n_u = (U_{HV})_{max}/(U_{LV})_{max}$ and n_{max}

Enter them in numerical order (Table 1 assumes increasing order from the top and n_u is supposed to be higher than n_1 but in some cases n_1 can be higher than or equal to n_u).

Prepare also a line for the principal tapping which, for the reasons reiterated in **2.4.3**(d), will be placed between the lines $n=n_1$ and $n=n_u$. Write 100 as the value of K_A, the value of n, namely n_p, being still undetermined.

b) Enter in the table the maximum voltage and current values for each winding as shown in Table 1,

   1) $(U_{LV})_{max}$ from n_{min} to n_u and $(U_{HV})_{max}$ from n_u to n_{max};

   2) $(I_{HV})_{max}$ from n_{min} to n_1 and $(I_{LV})_{max}$ from n_1 to n_{max}.

c) Complete the table with those missing values of voltage and current marked (†) in the table. The appropriate voltage or current value is deduced from the value of voltage or current of the other winding and of the value of voltage ratio n. The tapping power is then calculated.

d) Choose the tapped winding and the principal tapping. From the definitions of the principal tapping and of the full power tappings, this is one of the full-power tappings, that is, one of the tappings ranging from the ‘ maximum voltage tapping ’ to the ‘ maximum current tapping ’.

   The simplest solution is to take the mean tapping if it is a full-power tapping or, if not, the full-power tapping which is the closest to the mean tapping.

e) The tapping factor K_A can then be calculated.

   $K_A = n/n_p$ if the tappings are on the HV winding; and

   $K_A = n_p/n$ if the tappings are on the LV winding.

TABLE 1 TAPPING QUANTITIES

(*Clause* 2.4.3)

n*	K_A	VOLTAGE		CURRENT		POWER	TAPPING DESIGNATION
		HV	LV	HV	LV		
(1)	(2) percent	(3)	(4)	(5)	(6)	(7)	(8)
n_{min}= ..	§	†	(U_{LV})max	(I_{HV})max	†	‡	Minimum voltage ratio tapping
n_i= ..	§	†	(U_{LV})max	(I_{HV})max	(I_{LV})max	Smax‡	Maximum current tapping
n_p=...¶	100	¶	(U_{LV})max	¶	(I_{LV})max	Smax	Principal tapping
n_u=...	§	(U_{HV})max	(U_{LV})max	†	(I_{LV})max	Smax†	Maximum voltage tapping
n_{max}=...	§	(U_{HV})max	†	†	(I_{LV})max	‡	Maximum voltage ratio tapping

*The table assumes $n_u > n_i$.

†To be completed with the appropriate values of voltage current, deduced from the voltage or current of the other winding and of the voltage ratio n.

‡Power is calculated from voltage and current values.

§After choosing the tapped winding and the principal tapping, tapping factors K_A are calculated.

¶To be filled in after choosing the principal tapping, that is, n_p.

Furthermore, n_p being known, the line ' principal tapping ' can be completed. This line gives the rated values of voltages, currents and power.

The table is thus complete.

NOTE—The preceding method generally leads to combined voltage variation. However, if n_u is equal to an extreme value of n, the category of voltage variation is 'constant flux voltage variation' of 'variable flux voltage variation', according to whether the maximum voltage tapping is the extreme plus tapping or the extreme minus tapping. Furthermore, if the maximum voltage tapping, without being the extreme plus tapping, is close enough to it, the combined voltage variation can be changed into constant flux voltage variation in order to simplify still more the specification of the tapping quantities (*see* **2.7**).

f) The various values can now be rounded off, particularly the rated power. This rounding off and the use of a suitable number of steps naturally affects somewhat the voltage and current values. Furthermore, the possibility of operation at voltages higher than the tapping voltage can be considered (*see* **2.6**).

When the preceding calculations have led to the choice of an extreme tapping as the maximum current tapping, it may be advisable to re-examine this choice as indicated in **A-4** of Appendix A.

g) For specification purposes, the table can be abbreviated, as the numerical data of the table can actually be obtained from the following more concentrated data, according to **3.4.2.1** of IS : 2026 (Part 4)-1977*.

   1) Rated power and rated voltages;
   2) Which winding is the tapped winding, and its tapping range;
   3) The number of tapping positions or the value of the tapping steps;
   4) Which tapping is the ' maximum voltage tapping ' with the corresponding tapping voltages; and
   5) Which tapping is the ' maximum current tapping '.

2.4.4 *Examples of Application of This Method*—Three examples are given in Appendix A.

2.5 Tapping Currents of Auto-Transformers

2.5.1 For separate winding transformers, **2.4.2**(c) considered two parameters corresponding to the maximum currents of the windings, namely $(I_{HV})_{max}$ and $(I_{LV})_{max}$. For auto-transformers, the windings to be considered are the series winding and the common winding. The maximum current of the series winding is equal to $(I_{HV})_{max}$, but the maximum current of the common winding is equal to the maximum value of the difference $(I_{LV} — I_{HV})$.

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*Specification for power transformers: Part 4 Terminal marking, tappings and connections (*first revision*).

For this reason, the ‘ maximum current tapping ’, based on $(I_{HV})_{max}$ and $(I_{LV})_{max}$ does not have the physical meaning it has for separate winding transformers (*see* **2.4.1**). As a consequence, it would in theory be inappropriate to base the current requirements on such a tapping, and a more elaborate specification of the tapping quantities would be needed.

However, in practice, auto-transformers can generally be treated in the same manner as separate winding transformers, provided it is verified that the common winding meets the standard temperature rise guarantees throughout the tapping range. This verification can normally be provided by calculation from one single temperature-rise test with the transformer connected on a suitable tapping.

An example is given in **A-5** of Appendix A.

2.6 Possibilities of Operation at Voltages Higher Than the Tapping Voltages — The possibilities of continuous operation at increased voltage at full current or at reduced current are given in **4.3** of IS : 2026 (Part 1)-1977*.

2.6.1 *Possibilities During Full-Current Operation* — As a general rule, the 5 percent overvoltage margin allowed in IS : 2026 (Part 1)-1977* is used to meet exceptional circumstances, for instance system voltages.

2.6.2 *Possibilities During Reduced Current Operation*—The purchaser may pecify that the transformer shall be capable of operation at voltages higher than the tapping voltage, for example, of operation at 110 percent of this voltage at no-load and at 108·75 percent at half-load.

2.7 Conversion of ‘ Combined Voltage Variation ’ into ‘ Constant Flux Voltage Variation ’ — The principle of this conversion is that the tapping voltage U_B of the untapped winding, instead of reaching its maximum value for only some tappings, retains this value for all the tappings. The voltage U_A of the tapped winding is no longer ‘ cut at the top ’.

Resulting from this conversion, voltages U_B and U_A, and thereby the tapping power, are increased for the whole of the former ‘ variable flux range ’.

The main advantage is simplification. Moreover, this conversion can also lead to a better indication of the overall voltage and power capability of the transformer when operated on those tappings of which the voltage and power have been increased.

On the other hand, this conversion may lead to abnormally high tapping voltages for these tappings, and also to needlessly increasing the requirements with regard to the ability to withstand short circuits.

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*Specification for power transformers: Part 1 General (*first revision*).

The conversion can also lead to difficulties with regard to temperature-rise requirements if, for ' combined voltage variation ', the ' maximum current tapping ' is in the ' variable flux range ' since the conversion leads to increasing the tapping voltages assigned to this tapping.

It should also be noticed that, in the latter case, the tapping power of the ' maximum current tapping ' is increased, which means that the rated power assigned to the transformer is increased (*see* Fig. 1).

As a conclusion, it is recommended that constant flux voltage variation (CFVV) be utilised every time the voltage increase that this implies does not exceed 5 percent. In other cases, the final choice between the combined voltage variation and the constant flux voltage variation (CFVV) will depend on the comparison of the advantages and disadvantages of each solution.

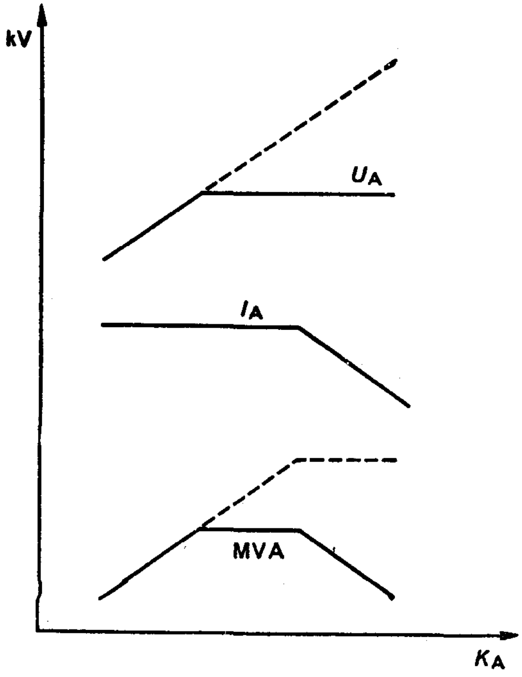


FIG. 1 EFFECT OF CONVERSION OF COMBINED VOLTAGE VARIATION TO CONSTANT FLUX VOLTAGE VARIATION

3. SELECTION OF WINDING CONNECTIONS FOR TRANSFORMERS FOR THREE-PHASE SYSTEMS

3.1 The selection of the connections for the windings of a three-phase transformer and single-phase transformers intended to be associated in a three-phase bank is determined by their service requirements, for instance parallel operation with other transformers, the provision of brought-out neutral points and any necessity of neutral loading.

3.2 The connections chosen influence the design of the transformer and the amount of material required. In certain cases, the type of magnetic circuit (that is, with or without magnetic return limbs) has also to be considered when choosing the connections.

3.3 The winding connections most commonly used are star, delta and zigzag or interconnected star. The star connection is particularly suitable for high-voltage windings with graded insulation, for windings to be equipped with on-load tap-changers, and when a neutral point is required for loading purposes. The delta connection is advantageous for high currents. The zigzag connection is, in general, only used for the low-voltage windings in transformers with low rated power, when the neutral point may be loaded for three-phase neutral electromagnetic couplers and for earthing transformers.

Table 2 contains a summary of the most important characteristics of these three connections.

4. PARALLEL OPERATION OF TRANSFORMERS IN THREE-PHASE SYSTEMS

4.0 General—Parallel operation applies to the operation of transformers with direct terminal-to-terminal connections for two of their windings. In the following, only two-winding transformers will be considered. In other cases, parallel operation should form the subject of a special study.

NOTE—For the purpose of this clause, a transformer with two main windings plus a stabilizing winding is considered as a two-winding transformer.

4.1 In order that two transformers can operate in parallel under the conditions specified above, the conditions as given in **4.2**, **4.3** and **4.4** have to be met for the pairs of windings to be connected in parallel.

4.2 Connection—The connections shall be compatible with each other:

a) Transformers of the same phase-angle relations, that is, having the same clock hour figure for the vector diagram, can be operated in parallel by connecting together, on the primary and secondary sides respectively, the terminals with the same symbol;

TABLE 2 CHARACTERISTICS OF CONNECTIONS

(*Clause* 3.3)

	STAR CONNECTION		DELTA CONNECTION	ZIGZAG CONNECTION
Loading capability of the neutral point	Depends on the connection of the other winding(s) and on the zero-sequence impedance(s) of the network(s) to which the transformer is connected (*see* 5.2)		—	Can be loaded with the rated current of the winding
	Either	Or		
Magnetizing currents	Third harmonic currents cannot flow (neutral isolated; no winding in delta connection present)	Third harnomic currents can flow in at least one winding of the transformer	Third harmonic currents can circulate in the delta-connected winding	—
Phase voltage	Contains third harmonic voltages*	Sinusoidal	Sinusoidal	—

*These third harmonic voltages are insignificant in three-phase core-type transformers with three limbs. In three-phase core-type transformers with five limbs, three-phase shell-type transformers and single-phase transformers connected together in three-phase banks, they may take on high values and lead to corresponding displacements of the netural point.

b) From the point of view of possibilities of operation in parallel when the clock hour figures are different, connections can be classified in groups :

Group I : clock hour figures 0, 4 and 8;

Group II : clock hour figures 6, 10 and 2;

Group III : clock hour figures 1 and 5; and

Group IV : clock hour figures 7 and 11.

c) The parallel operation of two transformers belonging to the same group is always possible under substantially balanced load conditions. If they have different clock hour figures, then the difference between the clock hour figures in the same group has always to be 4 or 8, that is, a difference in phase angle of 120° or 240°, which is the same as between two lines of a three-phase system. The terminals having the same marking on the two transformers will then be connected together on the one side (high-voltage or low-voltage), whilst on the other side, the terminals will be connected in cyclic rotation according to the appropriate diagram in Fig. 2.

d) A transformer of Group III can be operated in parallel with a transformer of Group IV if the phase sequence of one transformer is reversed relative to that of the other. The change of terminal connections is as given in Fig. 3.

e) The parallel operation of two transformers belonging to different groups (the III and IV combination mentioned above excepted) is not possible. The following combinations therefore cannot be operated in parallel :

Group I : with II or with III or with IV;

Group II : with I or with III or with IV;

Group III : with I or with II; and

Group IV : with I or with II.

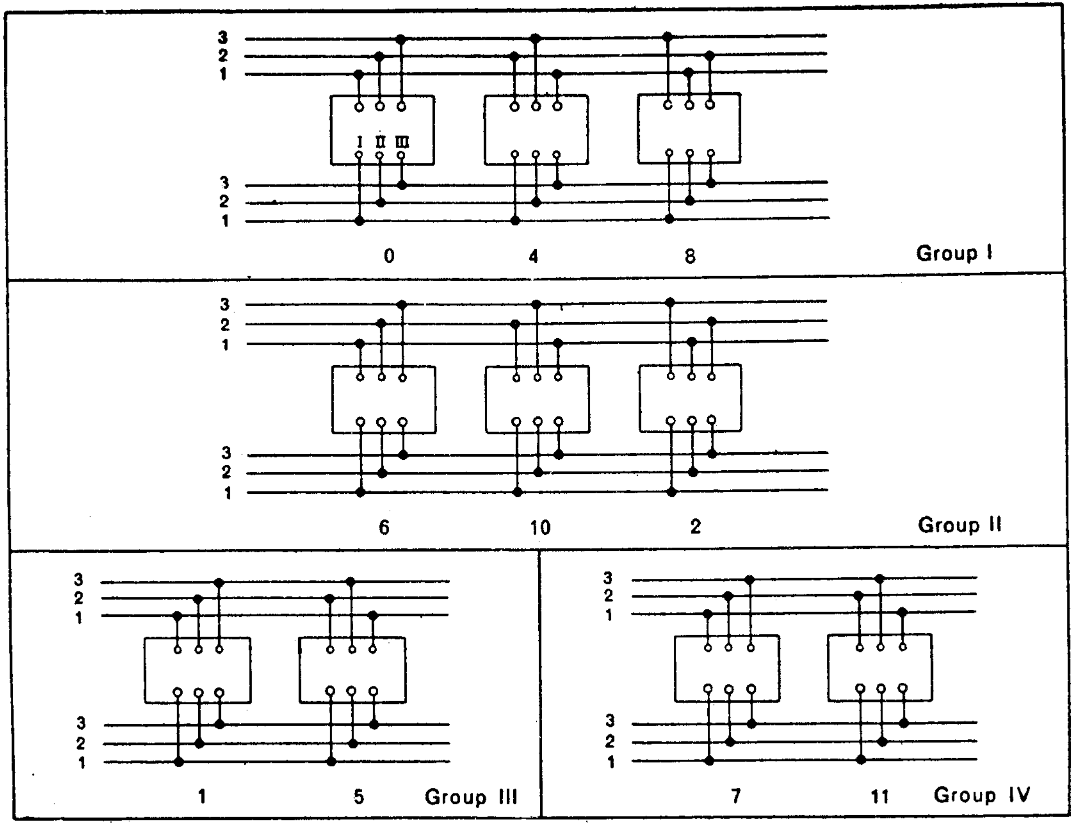
NOTE 1 — In the case of parallel operation of transformers having different connection symbols satisfactory operation in the above conditions is understood for the case of virtually balanced loads.

The case of unbalanced loads should form the subject of a special study.

NOTE 2 — It is also advisable to consider the effect of the connections on the behaviour of the transformers working in parallel during single phase-to-earth faults.

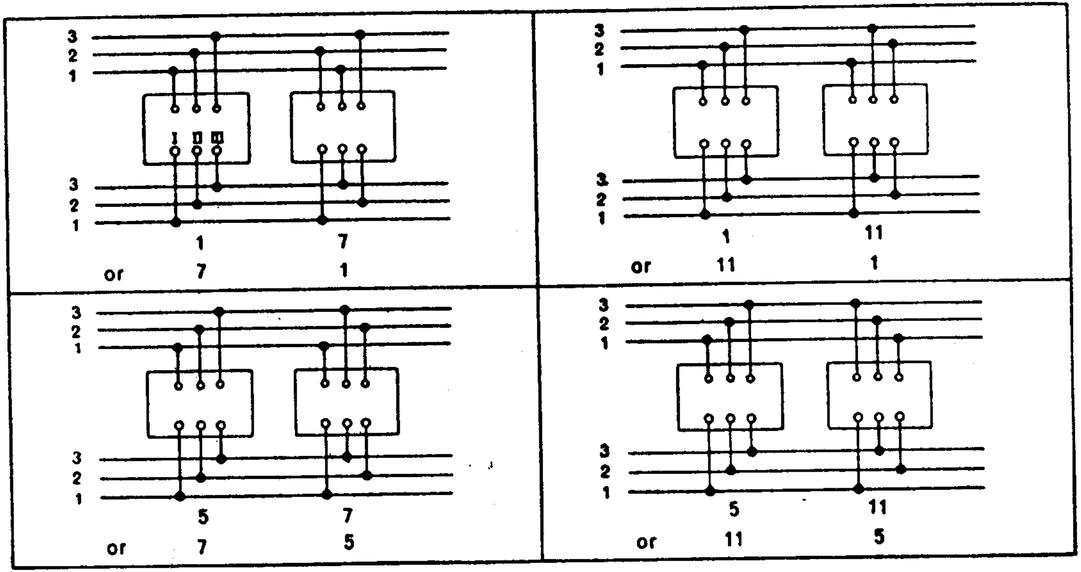
4.3 Voltage Ratios—The voltage ratios shall be equal within the limits of the permissible tolerances.

NOTE — However, if the conditions given in **4.4** are not complied with, the load sharing may be improved by a difference between the voltage ratios of the two transformers. The efficacy of this mean varies with the power factor of the circuit supplied.



NOTE — The larger figures at the foot of each diagram give the clock-hour figures.

FIG. 2 PARALLEL OPERATION OF TRANSFORMERS OF THE SAME GROUP



NOTE — The large figures at the foot of each diagram give the clock-hour figures.

FIG. 3 PARALLEL OPERATION OF TRANSFORMERS OF GROUPS III AND IV

4.4 Short-Circuit Impedance, or Impedance Voltage, and load Sharing

4.4.1 *Transformers Without Tappings and Tapped Transformers Whose Tapping Does Not Exceed ±5 percent* — For transformers without tappings, the impedance voltages at rated current shall be equal within the limits of the permissible tolerances. The same condition applies to tapped transformers whose tapping range does not exceed ± 5 percent.

NOTE 1 — This assumes that the rated voltages of the two transformers are equal, not merely the rated voltage ratio. The ratio Z_{k_1} / Z_{k_2} of the ohmic short-circuit impedances is then equal to the inverse ratio S_{n_2} / S_{n_1} of the rated powers, since,

$$Z_k = \frac{u_z}{100} \cdot \frac{U_N^2}{S_N},$$

where U_N is the rated voltage

Therefore, the load is shared between the two transformers in proportion to their respective rated powers.

NOTE 2—To be strictly correct, the resistive and reactive components of the impedances should be separately considered, but in practice it is generally sufficient to consider only the total impedance value.

NOTE 3—When considering parallel operation of two transformers having widely different rated powers (particularly if the ratio of the rated powers is not between 0·5 and 2) caution should be exercised, since variations in load sharing, even though within the limits set by the above-mentioned tolerances, may nevertheless result in overloading of the smaller transformer. This can be caused either by operation of the tolerances in opposite directions on the two transformers or because of differences in the relative values of the resistive and reactive components of impedance referred to in Note 2.

4.4.2 *Tapped Transformers Whose Tapping Range Exceeds ±5 percent* — For acceptably equal load sharing between two transformers of equal rated power, operating on full power tappings, the short-circuit impedances in ohms per phase, referred to the same side of each transformer, should have the same value with a tolerance of ± 10 percent (in other words each of the two values should not differ more than 10 percent from their mean value). Bigger differences between the two impedances are sometimes acceptable but a special study is then needed.

When considering two transformers of unequal rated powers, operating on full power tappings, the total load will be shared in the inverse ratio of their ohmic impedances, that is :

$$Q_1 = \frac{Z_{k_2}}{Z_{k_1} + Z_{k_2}} Q \text{ and } Q_2 = \frac{Z_{k_1}}{Z_{k_1} + Z_{k_2}} Q \text{ whence } \frac{Q_1}{Q_2} = \frac{Z_{k_2}}{Z_{k_1}}$$

where Q is the total load, Z_k the ohmic impedance and suffices 1 and 2 refer to the respective individual quantities for each transformer.

Each transformer will take a part of the total load acceptably in proportion to its rating if Z_{k_2}/Z_{k_1} is approximately equal to the ratio

S_{N_1}/S_{N_2} of the two rated powers, in other words if the product Z_k S_N has the same value, with a tolerance of ±10 percent for the two transformers.

In the particular case of both transformers being on the principal tapping, where the impedance can be quoted as a percentage voltage (impedance voltage at rated current) instead of the short-circuit impedance in ohms per phase, each transformer will take a part of the total load acceptably in proportion to its rating if the impedance voltages at rated current of the two transformers have the same value with a tolerance of ± 10 percent.

If at least one transformer operates on a reduced power tapping, the tapping power S_t of each transformer is to be used instead of the rated power S_N and the load sharing will then be acceptable if the product Z_k S_t has the same value, with a tolerance of ±10 percent for the two transformers (at the tappings used).

NOTE 1—In all the above text it is asssumed that the tapping voltages of the two transformers are equal at the tappings used. If this should not be the case, it is not the rated powers or tapping powers which should be considered but the tapping currents (I_t).

At the tappings used the product Z_k I_t of short-circuit impedance and tapping current should have the same value, with a tolerance of ± 10 percent for the two transformers (all values of Z_k and I_t being referred to the same side).

NOTE 2—To be strictly correct, the resistive and reactive components of the impedances should be separately considered, but in practice it is generally sufficient to consider only the total impedance value.

NOTE 3—When considering parallel operation of two transformers having widely different rated powers (particularly if the ratio of the rated powers is not between 0·5 and 2), caution should be exercised, since variations in load sharing, even though within the limits set by the abovementioned tolerances, may nevertheless result in over-loading of the smaller transformer. This can be caused either by operation of the tolerances in opposite directions on the two transformers or because of differences in the relative values of the resistive and reactive components of impedance referred to in Note 2.

5. LOADING CAPABILITY OF THE NEUTRAL POINT OF WINDING IN STAR OR ZIGZAG CONNECTION

5.1 General — The neutral point of star or zigzag-connected windings may be loaded under the conditions given below.

5.1.1 If, under neutral loading conditions, the current in the phase-windings does not exceed the values corresponding to rated or tapping currents, the normal temperature-rises apply.

5.1.2 If these currents are exceeded in any phase-winding, as they may be if neutral loading — for example, with an arc-suppression coil — is added to a winding already symmetrically fully loaded, this may lead to the normal temperature-rises being exceeded in any winding which carries zero-sequence current, and also in the oil.

5.2 Star Connection—The loading capability of the neutral point depends on whether or not the zero-phase sequence current flowing in the winding under consideration is balanced by corresponding ampere-turns in at least one of the other windings of the transformer. The following cases should be distinguished.

5.2.1 *Star-Star Connection Without an Additional Winding in Delta Connection, the Neutral Point of the Primary Winding Being Isolated :*

a) Three-phase shell-type transformers, three-phase core-type transformers with five limbs and banks of three single-phase transformers :

   The loading of the neutral point of the secondary winding should be avoided.

b) Three-phase core-type transformers with three limbs :

   1) The neutral point of the secondary winding may be loaded through an arc-suppression coil with 25 percent of the rated current for a highest duration of 1·5 hours or with 20 percent of the rated current for a duration of not more than 3 hours. This causes, besides considerable stray losses in the transformer, a zero-sequence voltage drop of about 5 percent to 10 percent of the line-to-neutral voltage.

   2) In three-phase systems with four-wire loads on the secondary winding, the neutral point may, with due regard to the voltage symmetry, for example, for lighting supply, be loaded continuously up to 10 percent of the rated current.

5.2.2 *Star-Star Connection Without an Additional Winding in Delta-Connection, the Neutral Point of the Primary Winding being Connected to the Neutral of the System* — If the zero-sequence impedance of the primary system is sufficiently small, the neutral point of the secondary winding may be loaded with the rated current of the winding.

5.2.3 *Star-Star Connection with an Additional Winding in Delta Connection (Third Winding or Stabilizing Winding)* — If the delta-connected winding is not loaded externally, the neutral point of star-connected windings may be loaded so as not to exceed the rated current of the delta-connected winding. For instance, if the additional winding is rated at one-third of the rating of the winding in star connection, one of the neutral points may be loaded with the rated current of its winding.

In the case of a winding in delta connection being loaded externally, the loading capability of the neutral points has to be determined separately for each case of loading.

5.2.4 *Star-Delta Connection or Delta-Star Connection*—The neutral point may be loaded with the rated current.

5.2.5 *Star-Zigzag Connection*—The neutral point of the star-connection winding may be loaded as described in **5.2.1**.

5.3 Zigzag Connection—The neutral point of a winding in zigzag connection can be loaded with the rated current because the required counter-ampere-turns of the zero-phase-sequence system will be produced in the winding itself.

NOTE—In the event of the line-to-earth faults on the connected systems, the earthed neutral points of windings in star or zigzag connection carry fault currents, the intensity of which has to be considered when designing the windings, choosing the neutral bushings and dimensioning their connections to the windings. Calculation of fault currents flowing in the neutral points requires information as to the earthing conditions of the systems and their impedances, the possible locations where faults may occur and the number of transformers connected in parallel.

In the case of a transformer with two windings in star connection joining two earthed systems, the calculation of the currents has to be carried out separately for faults on each system.

The possibility of a bushing flashover on a neutral point which is isolated should not be ignored.

6. CALCULATION OF VOLTAGE DROP (OR RISE) FOR A SPECIFIED LOAD CONDITION

6.1 Two-Winding Transformers — The voltage drop (or rise) with load between no-load and rated symmetrical load of any assumed value and power factor can be calculated from the measurement of the short-circuit impedance (or, for the principal tapping, of impedance voltage at rated current) and the load loss [*see* **16.4** of IS : 2026 (Part 1)-1977*].

6.1.1 *Transformer Untapped or Connected on the Principal Tapping*—The no-load voltage of a winding is assumed to be its rated voltage :

let u_Z = impedance voltage at rated current as percentage of rated voltage, consisting of components ;

u_r = resistance voltage at rated current as percentage of rated voltage = load loss as percentage of rated power of transformer;

u_X = reactance voltage at rated current as percentage of rated voltage

$$u_X = \sqrt{u_Z^2 - u_r^2}$$

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*Specification for power transformers: Part 1 General (*first revision*).

The voltage drop (or rise) as a percentage of the rated voltage, for an assumed fractional load value n and power-factor cos ϕ, is :

$$U_{\phi n} = nU'_{\phi} + \frac{1}{2}\,\frac{(nU''_{\phi})^2}{10^2} + \frac{1}{8}\,\frac{(nU''_{\phi})^4}{10^6} + \dots\dots\dots$$

where

$U'_{\phi} = u_r \cos\phi + u_x \sin\phi$, and

$U''_{\phi} = u_r \sin\phi - u_x \cos\phi$.

If u_Z is less than 20 percent, the third term may be ignored. If u_Z is less than 4 percent, the second term may also be ignored.

6.1.2 *Transformer Connected on a Tapping Other Than the Principal Tapping* — The no-load voltage of a winding is assumed to be its tapping voltage.

For a given tapping the equation in **6.1.1** can be used to calculate the voltage drop (or rise) expressed as a percentage of the tapping voltage if u_Z, u_r and u_x are replaced by the quantities u_{Zt}, u_{rt} and u_{xt} respectively corresponding to that tapping :

$$u_{zt} = 100\ Z_{kt}\ \frac{S_t}{U_t^2}$$

where

Z_{kt} = short-circuit impedance at this tapping related to a given winding,

U_t = tapping voltage of this winding, and

S_t = tapping power

u_{rt} is equal to the load loss related to the tapping current expressed as a percentage of the tapping power

$$u_{xt} = \sqrt{u_{zt}^2 - u_{rt}^2}$$

For calculating the fractional value n of the load, the reference current should be the tapping current.

6.2 Three-Winding Transformers

6.2.1 *Application of Formulae*—The formulae given above for two-winding transformers can be applied to three-winding transformers, and their voltage drop (or rise) calculated with an accuracy comparable to that of the data available by assuming the currents in the windings remain constant, both in magnitude and phase angle, even though the output terminal voltages change, due to voltage drop or rise, from their no-load values.

On a three-winding transformer the open-circuit no-load voltage of a winding will change with current in the other windings (even though it remains itself unloaded).

Therefore the voltage drop (or rise) of a winding on a three-winding transformer is expressed with reference to its no-load voltage obtained from the voltage ratio.

For the frequent case of two output windings (W_2 and W_3) and one input winding (W_1), the voltage drop (or rise) is usually required for three loading conditions, namely :

W_2 only loaded;

W_3 only loaded;

both W_2 and W_3 loaded.

For each condition, two separate figures should be quoted, that is, the voltage drop (or rise) of each output winding W_2 and W_3 (whether carrying current or not) for constant voltage supplied to the first winding W_1.

NOTE—The voltage drop (or rise) between W_2 and W_3 relative to each other for this simple and frequent case is implicit in the values W_1 to W_2 and W_1 to W_3, and nothing is gained by expressing it separately.

6.2.2 *Data Required*—The data required are the following quantities, determined for each pair of windings and related to the same basic apparent power (S_b) which can conveniently be the tapping power (rated power for the principal tapping) of the winding of the lowest rating (these data should be determined from the transformer as built).

a) Load loss corresponding to the power S_b and designated hereafter as w;

b) Impedance voltage (principal tapping) or the following quantity u'_{zt}

$$u'_{zt} = 100 \, , Z_{kt} \frac{S_b}{U_t^2}$$

where

u'_{zt} = impedance voltage as percentage of the given winding;

Z_{kt} = short-circuit impedance at this tapping related to a given winding; and

U_t = tapping voltage of this winding.

c) Resistance voltage (principal tapping) or the following quantity u'_{rt}.

$$u'_{rt} = 100 \frac{W}{S_b}$$

d) Reactance voltage (principal tapping) or the following quantity u'_{xt}.

$$u'_{xt} = \sqrt{u'^2_{zt} - u'^2_{rt}}$$

From the data an equivalent circuit is derived as shown in Fig. 4.

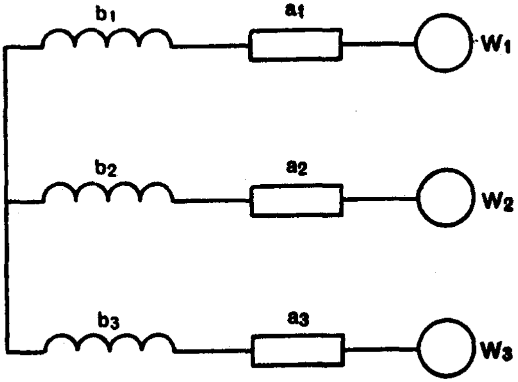


FIG. 4 EQUIVALENT CIRCUIT

6.2.3 *Equivalent Circuit for Three-Winding Transformer* — The equivalent circuit is derived as follows :

let a_{12} and b_{12} be respectively the percentage resistance and reactance voltages, or more generally, the quantities u'_{rt} and u'_{xt}, referred to the basic power and obtained on a test, short-circuiting either winding W_1 or W_2 and supplying the other, with the third winding W_3 on open circuit;

let a_{23} and b_{23} similarly apply to a test on the pair of windings W_2 and W_3 (with W_1 on open circuit);

let a_{31} and b_{31} similarly apply to a test on the pair of windings W_3 and W_1 (with W_2 on open circuit);

let d = the sum ($a_{12} + a_{23} + a_{31}$);

let f = the sum ($b_{12} + b_{23} + b_{31}$).

Then the mathematical values to be inserted in the equivalent circuit are :

arm W_1 $a_1 = d/2 - a_{23}$ $b_1 = f/2 - b_{23}$
arm W_2 $a_2 = d/2 - a_{31}$ $b_2 = f/2 - b_{31}$
arm W_3 $a_3 = d/2 - a_{12}$ $b_3 = f/2 - b_{12}$

It is to be noted that some of these mathematical quantities may be negative or may even be zero (depending on the actual physical relative arrangement of the windings on the core). For the desired loading conditions, the power operative in each arm of the equivalent circuit is determined and the voltage drop (or rise) of each arm is calculated separately. The voltage drop (or rise) with respect to the terminals of any pair of windings is the algebraic sum of the voltage drops (or rises) of the corresponding two arms, of the equivalent circuit.

6.2.4 *Detailed Procedure*—The detailed procedure to be followed in the case of two output windings and one supply winding is, as a first approximation, as follows :

a) Determine the power in each winding corresponding to the loading being considered : for the output windings W_2 and W_3 this is the specified loading under consideration;

b) Deduce n_2 and n_3 where n is the ratio of the actual loading to the basic power used in the equivalent circuit for each arm; and

c) The input power of the winding W_1 should be taken as the vectorial sum of the outputs from the windings W_2 and W_3. The corresponding power-factor and quadrature factor (sin ϕ) are deduced from the in-phase and quadrature components.

When greater accuracy is required in the determination of the apparent power of the winding W_1, an addition should be made to the abovementioned vectorial sum, as follows : add to the quadrature component, to obtain the effective input power to winding W_1 the following quantities :

$$\text{(the output power from winding } W_2 \text{)} \times \frac{b_2}{100} \times n_2$$

$$\text{plus (the output power from winding } W_3 \text{)} \times \frac{b_3}{100} \times n_3$$

A still more accurate solution is obtained by adding the corresponding quantities ($a \times n \times$ output power) to the in-phase component of the vectorial sums of the outputs, but the difference is rarely appreciable.

6.2.4.1 *Method of calculation*—Apply the formula of **6.1.1** separately to each arm of the network taking separate values of n for each arm as defined above.

6.2.4.2 *Voltage drop (or rise)*—To obtain the voltage drop (or rise) between the supply winding and either of the loaded windings, and the separate voltage drops (or rises) determined for the corresponding two arms, noting that one of these may be negative (note that the summation is algebraic, but not vectorial).

NOTE—A positive value for the sum determined indicates a voltage drop from no-load to the loading considered, while a negative value for the sum indicates a voltage rise.

Repeat the operation described above for the other loaded winding.

6.2.5 *Supply to Two Windings* — In the case of a supply to two windings and output from one winding, the above procedure can be applied if the division of loading between the two supplies is known.

6.2.6 *Auto-Transformers*—The above procedure is applicable to auto-transformers if the equivalent circuit is based on the effective impedances and load losses measured at the terminals of the auto-transformer.

7. LOSS CALCULATION OF A THREE-WINDING TRANSFORMER

7.1 A method of calculation of winding losses for a three-winding transformer is given in Appendix B.

8. INHERENT VOLTAGE REGULATION

8.1 A method of calculation of inherent voltage regulation of two and three winding transformers is given in Appendix C.

APPENDIX A

(*Clauses* 2.4 *and* 2.5)

EXAMPLES OF THE METHOD BASED ON THE MAXIMUM CURRENT AND MAXIMUM VOLTAGE OF EACH WINDING

A-1. FIRST EXAMPLE

A-1.1 Step-down transformer supplied with a variable voltage and delivering a variable power with a secondary voltage which increases with the load.

The transformer is assumed to supply a 20 kV system from a 115 kV system :

a) applied voltage ranging from 107 kV to 123 kV; and

b) load conditions ranging between the two following extreme duties :

A-1.1.1 *Full-Current Duty*

$I_{LV} = 1\ 000$ A.

On-load LV voltage : 21 kV, which gives, after correction for the voltage drop, a 'no-load voltage' equal to 22 kV (consequently, n varies from $123/22 = 5{\cdot}591$ to $107/22 = 4{\cdot}864$ and $(I_{HV})_{max} = 1\ 000/4{\cdot}864 = 205{\cdot}6$ A).

A-1.1.2 *No Load Duty*

$I_{LV} = 0$· LV voltage : 20 kV.

(n varies from 123/20 to 107/20, that is, from 6·15 to 5·35).

For the intermediate duties, it will be sufficient to consider the half-current duty $I_{LV} = 500$ A. Corresponding ' no-load ' LV. voltage : 21 kV.

A-1.1.3 The six required quantities are now determined :

First, the HV maximum voltage is : $(U_{HV})_{max} = 123$ kV.

Then, the 'no-load' duty gives :

$n_{max} = 123/20 = 6{\cdot}15.$

Then the full-current duty gives the values of the last four quantities :

a) $n_{min} = 107/22 = 4{\cdot}864$;

b) $(U_{LV})_{max} = 22$ kV;

c) $(I_{LV})_{max} = 1\ 000$ A and

$(I_{HV})_{max} = 205{\cdot}6$ A.

whence

a) the maximum voltage tapping : $n_u = 123/22 = 5{\cdot}591$;

b) the maximum current tapping : $n_i = 1\ 000/205{\cdot}6 = 4{\cdot}864$ (this tapping is the same as the tapping with the minimum voltage ratio).

From this the tapping quantities given in Table 3, are deduced except those between parenthesis, relating to the col 2 'K_A' and the line 'principal tapping'. If the tappings are located on the high voltage winding if the principal tapping is the mean tapping $n = 5{\cdot}507$, which is a full power tapping, the values between brackets can be calculated and Table 3 can be completed. Figure 5 is a graph illustrating Table 3.

The table can be summarized as follows for specification purposes :

a) Rated power : 38 MVA;

b) Rated voltages : 121·15 kV and 22·0 kV;

c) Tappings on high voltage winding (tapping range ± 11·5 percent);

d) Maximum voltage tapping : K_A = 101·5 percent, and

e) Maximum current tapping : extreme minus tapping.

The specification should also include the number of tapping positions, or the value of the tapping step (this can lead to slight changes in the previous values).

TABLE 3 EXAMPLE NO. 1 TAPPING QUANTITIES AS A FUNCTION OF THE VOLTAGE RATIO n AND OF THE TAPPING FACTOR K_A. TAPPINGS ON THE HIGH VOLTAGE WINDING

(*Clause* A-1)

(Abbreviations : Incr.=increases; Decr.=decreases)

n	K_A*	VOLTAGES		CURRENTS		POWER	TAPPING DESIGNATION
		HV	LV	HV	LV		
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	percent	kV	kV	A	A	MVA	
4.864†	(88·5)	107	22	205·6	1 000	$22\sqrt{3}$†	Maximum current tapping
Incr.†	Incr.	Incr.	22	Decr.	1 000	$22\sqrt{3}$†	
(5·507)†	100	(121·15)	22	(181·6)	1 000	$22\sqrt{3}$†	Principal topping
Incr.†	Incr.	Incr.	22	Decr.	1 000	$22\sqrt{3}$†	
5·591†	(101·5)	123	22	178·8	1 000	$22\sqrt{3}$†	Maximum voltage tapping
Incr.	Incr.	123	Decr.	Decr.	1 000	Decr.	
6·150	(111·5)	123	20	162·7	1 000	$20\sqrt{3}$	

NOTE—The values between parenthesis are those which are known only after the principal tapping and the tapped winding have been chosen.

*The mean tapping n=5·507, which is a full-power tapping, has been chosen as the principal tapping (K_A=100).

†The tappings ranging from n=4·864 to n=5·591, are full-power tappings, (U_{LV} maximum and I_{LV} maximum).

A-2. SECOND EXAMPLE

A-2.1 In the previous example, the 'maximum current tapping' was the same as the extreme minus tapping. The second example corresponds to the case in which this 'maximum current tapping' is distinct. Another difference from Example No. 1 is that the principal tapping cannot be the mean tapping because the latter is not a full-power tapping.

The example chosen is a step-down transformer connecting a 400 kV system to a 132 kV system, supplied at a voltage varying from 380 kV to 420 kV and which has to be capable of delivering, at a voltage varying from 128 kV to 136 kV, a load between the two following limits :

A-2.1.1 *Full Load Operation*—The power absorbed at the primary terminals is 300 MVA. The voltage drop is 5·7 percent (8 kV) and consequently the LV 'no-load' voltage ranges from 136 kV to 144 kV.

A-2.1.2 *No-Load Operation*—LV voltage ranging from 128 kV to 136 kV.

A-2.1.3 The six required quantities are now determined :

First $(U_{HV})_{max} = 420$ kV.

The ' no-load operation ' gives :

a) $n_{max} = 420/128 = 3{\cdot}281$;

The 'full-load operation' gives the other four required values :

b) $n_{min} = 380/144 = 2{\cdot}639$;

c) $(U_{LV})_{max} = 144$ kV;

d) $(I_{HV})_{max} = 456$ A (300 MVA at 380 kV); and

e) $(I_{LV})_{max} = 1\ 273$ A (300 MVA at 136 kV).

whence:

f) maximum voltage tapping : $n_u = 420/144 = 2{\cdot}917$; and

g) maximum current tapping : $n_i = 1\ 273/456 = 2{\cdot}792$.

This gives, as a function of the voltage ratio, the tapping quantities of Table 4 except the values between parentheses of col 2 ' K_A ' and of the line ' principal tapping '.

It is now assumed that the tapped winding is the HV winding. The mean tapping which corresponds to $n = 2{\cdot}96$ is not a full-power tapping. The closest full-power tapping is the ' maximum current tapping ' which corresponds to $n = 420/144 = 2{\cdot}917$. This tapping will be chosen as the principal tapping ($n_p = 2{\cdot}917$).

A-2.1.4 It is then possible to complete Table 4, Fig. 6 is a graph illustrating Table 4. The table can be summarised as follows for specification purposes :

a) Rated power : 318 MVA;

b) Rated voltages : 420 kV and 144 kV;

c) Tappings on HV winding (tapping range $+12{\cdot}5$ percent $-9{\cdot}5$ percent);

d) Maximum voltage tapping : principal tapping; and

e) Maximum current tapping : $K_A = 95{\cdot}7$ percent.

The specification should also include the number of tapping positions or the value of the tapping step (this can lead to slight changes in the previous values).

A-3. THIRD EXAMPLE

A-3.1 Corresponding to more complex load conditions :

The load conditions are as for Example No. 2 with the addition of a step-up condition with a reduced value of the power absorbed by the primary winding limited to 200 MVA. In this condition the LV applied voltage varies from 128 kV to 136 kV and the HV ' no-load voltage ', taking into an account a voltage drop of 4 percent, varies from 395 kV to 437 kV.

In comparison with Example No. 2, two of the six basic quantities of the calculation are modified :

a) $(U_{HV})_{max}$, which increases and becomes 437 kV;

b) n_{max}, which increases and becomes 437/128.

Figure 6 shows the curves of tapping voltage, current and power. They are identical to those of Example No. 2 for $K_A < 100$ percent, but for $K_A > 100$ percent divergences from Example No. 2 are shown by broken lines (it has been assumed that the tapping $n = 420/144$ was still used as the principal tapping).

A-4. ADDITIONAL INFORMATION RELATING TO THE USE OF ' MAXIMUM CURRENT TAPPING ' OTHER THAN THE EXTREME TAPPINGS

A-4.1 Even in a case such as Example No. 1, it may be judicious to use, in the final specification of the tapping quantities, a ' maximum current tapping' other than an extreme tapping.

In particular, if the extreme tapping is seldom used (for instance, if it has to be used only for extreme and rare system voltage conditions), it may be advisable to permit for this tapping a temperature rise slightly exceeding the guaranteed limit, by choosing another tapping as the 'maximum current tapping' and thereby avoiding needless oversizing

A-5. FOURTH EXAMPLE, SPECIFICATION OF THE TAPPING CURRENTS OF AN AUTO-TRANSFORMER (Fig. 7)

A-5.1 This example is the same as Example No. 2 except that the transformer is now an auto-transformer.

A-5.2 The simplest solution is to specify the same tapping currents as for the separate winding transformer. This leads to the curves S_1 (thick lines) of Fig. 7 : the LV and series currents are the same as the LV and HV currents of Table 4 and Fig. 6, the current in the common winding is equal to $I_{LV} - I_{series}$ and increases when n increases.

TABLE 4 EXAMPLE NO. 2 — TAPPING QUANTITIES AS A FUNCTION OF THE VOLTAGE RATIO n AND OF THE TAPPING FACTOR K_A. TAPPINGS ON THE HV WINDING

(*Clause* A-5)

(Abbreviations : Incr. = increases; Decr. = decreases)

n	K_A*	VOLTAGE		CURRENT		POWER	TAPPING DESIGNATION
		HV	LV	HV	LV		
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	percent	kV	kV	A	A	MVA	
2·639	(90·5)	380	144	456	1 200	300	
Incr.	Incr.	Incr.	144	456	Incr.	Incr.	
2·792†	(95·7)	402	144	456	1 273	318†	Maximum current tapping
Incr.†	Incr.	Incr.	144	Decr.	1 273	318†	
2.917†	(100)	420	144	438	1 273	318†	Maximum voltage tapping and principal tapping
Incr.	Incr.	420	Decr.	Decr.	1 273	Decr.	
3·281	(112·5)	420	128	388	1 273	282	

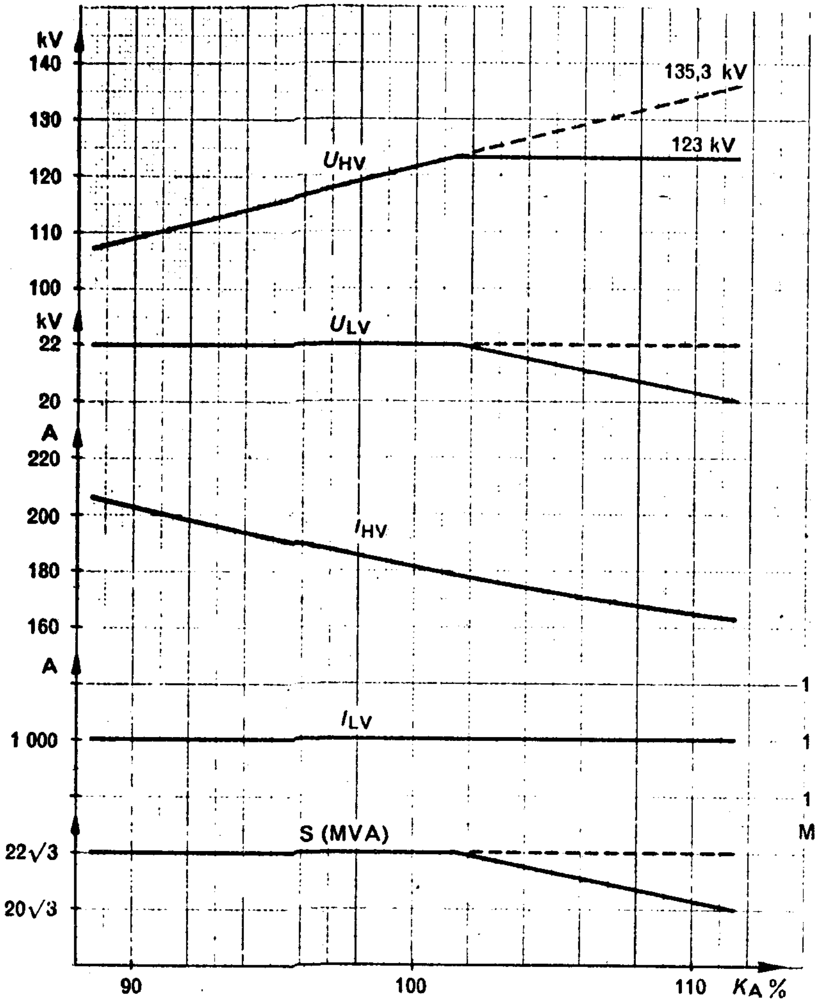
NOTE — The values between parenthesis are those which are known only after the principal tapping and the tapped winding have been chosen.

*The mean tapping $n = 2·96$ is not a full-power tapping. The tapping chosen as the principal tapping is the full power tapping which is closest to the mean tapping (which is here the 'maximum voltage tapping').

†The tappings ranging from $n = 2.792$ to $n = 2·917$ are the full-power tappings (U_{LV} and I_{LV} maximum).

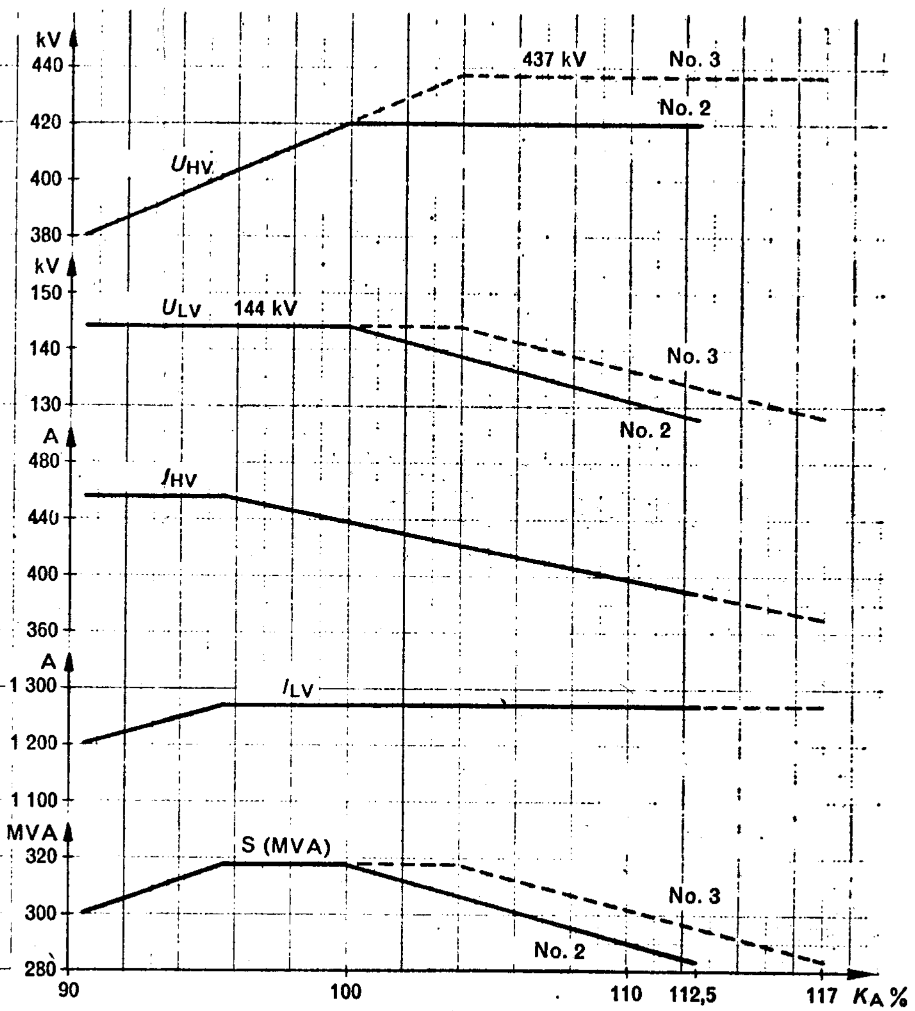
A-5.3 Considering the possible disadvantages of this solution :

a) The tappings above $n = 420/136 = 3·088$ are intended for operation at reduced load (no-load for n_{max}) : see the thin lines marked 'load'. Thus the real maximum value of I_{common} is 861 A and consequently the solution S_1, which gives 885 A, leads in theory to a needless oversizing of the transformer.



NOTE — The broken line for the highest values of K_A corresponds to C. F. V. V.

FIG. 5 EXAMPLE No. 1



NOTE — Above $K_A = 100\%$, Example No. 2 corresponds to the continuous line and Example No. 3 to the broken line.

FIG. 6 EXAMPLES No. 2 AND 3

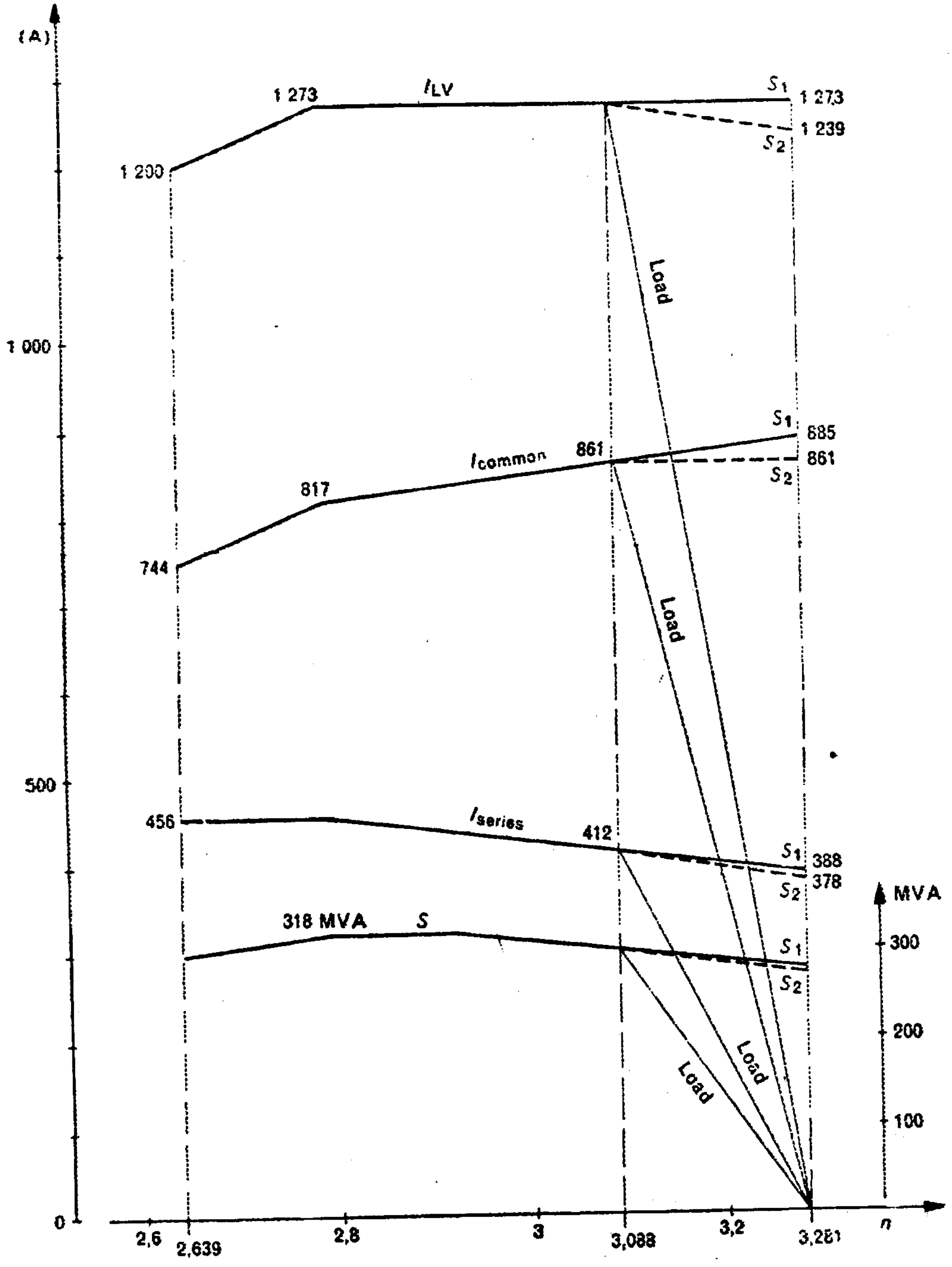


FIG. 7 EXAMPLE NO. 4 SPECIFICATION OF THE TAPPING CURRENTS OF AN AUTO-TRANSFORMER

b) The lines S_2 (broken lines), which differ from S_1 for the above-mentioned tappings, show a solution which would avoid this over-estimation of $(I_{common})_{max}$, I_{common} being limited to 861 A, but would lead to more complicated current requirements.

c) Theoretically, the solution S_2 is more appropriate to the auto-transformer than S_1. However, the differences between S_1 and S_2 are small, 2·7 percent for $(I_{common})_{max}$, and it can be judicious, in such a case, to use the same simple requirements as for a separate winding transformer.

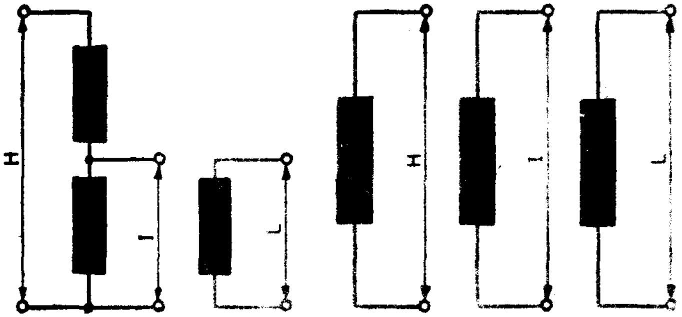
NOTE—With the solution S_1 the maximum temperature-rise of the common winding probably occurs on the highest tapping ($n = n_{max}$). With the solution S_2, it probably occurs on the tapping $n = 3·088$, beyond which I_{common} is limited to 861 A.

APPENDIX B

(*Clause* 7.1)

LOSS CALCULATION OF THREE-WINDING TRANSFORMER

B-1. A three-winding transformer can have 3 separated windings, namely, high voltage winding (H), intermediate voltage winding (I), low voltage winding (L) or two windings having a common part and a third low voltage winding (auto-transformer). Single phase representation of the two types is given in Fig. 8.



Auto Transformer Separate Winding Transformer

FIG. 8 THREE-WINDING TRANSFORMERS

B-2. Load losses are measured between windings taken in pairs according to **16.4** of IS : 2026 (Part 1)-1977* as below :

a) Between H and I (P_{HI})

---

*Specification for power transformers : Part 1 General (*first revision*).

b) Between I and L ($P_{I/L}$)

c) Between H and L ($P_{H/L}$)

All loss measurements are converted to a common rated kVA base preferably of H.

B-3. Applying the principle of 3 winding, losses corresponding to H, I and L are separated out as given below :

$$P_H = \frac{1}{2}\left(P_{H/I} + P_{I/L} + P_{H/L}\right) - P_{I/L}$$
$$P_I = \frac{1}{2}\left(P_{H/I} + P_{I/L} + P_{H/L}\right) - P_{H/L}$$
$$P_L = \frac{1}{2}\left(P_{H/I} + P_{I/L} + P_{H/L}\right) - P_{H/I}$$

B-4. Three winding losses are computed as under :

$$P = P_H \frac{(\text{Rated kVA of } H)^2}{(\text{Base kVA})} + P_I \frac{(\text{Rated kVA of } I)^2}{(\text{Base kVA})} + P_L \frac{(\text{Rated kVA of } L)^2}{(\text{Base kVA})}$$

APPENDIX C

(*Clause* 8.1)

CALCULATION OF INHERENT VOLTAGE REGULATION

C-1. TWO WINDING TRANSFORMERS

C-1.1 The inherent voltage regulation from no-load to a load of any assumed value and power factor may be computed from the impedance voltage and corresponding load loss measured with rated current in the windings as follows :

Let

I = rated current in winding excited;

E = rated voltage of winding excited;

I_{SC} = current measured in winding excited;

E_{ZSC} = voltage measured across winding excited (impedance voltage);

P_{SC} = watts measured across winding excited;

E_{XSC} = reactance voltage = $\sqrt{E^2_{ZSC} - {\frac{P_{SC}}{I_{SC}}}^2}$;

P = P_{SC} corrected to 75°C, and from current I_{SC} to I;

$E_x = E_{xsc} \times \dfrac{I}{I_{sc}}$;

$E_r = \dfrac{P}{I}$;

$E_x\% = 100\ E_x/E$;

$E_r\% = 100\ E_r/E$;

$n = I_a/I$; and

I_a = current in the winding excited during the short circuit test corresponding to that obtained when loading at the assumed load on the output side and with rated voltage on the input side.

C-1.2 For rated load at unity power factor, the percentage regulation is approximately equal to :

$$E_r\% + \frac{(E_x\%)^2}{(200)}$$

C-1.3 For rated load at any power factor cos ϕ, the percentage regulation is approximately equal to :

$$E_r\% \cos\phi + E_x\% \sin\phi + \frac{(E_x\% \cos\phi - E_r\% \sin\phi)^2}{200}$$

C-1.4 For any assumed load other than rated load and unity power factor, the percentage regulation is approximately equal to :

$$n.E_r\% + \frac{(n.E_x\%)^2}{200}$$

C-1.5 For any assumed load other than rated load and at any power factor cos ϕ, the percentage regulation is approximately equal to :

$$n.E_r\% \cos\phi + n.E_x\% \sin\phi + \frac{(n.E_x\% \cos\phi - n.E_r\% \sin\phi)^2}{200}$$

C-1.6 The above formulae are sufficiently accurate for transformers covered by this specification.

C-2. THREE WINDING TRANSFORMERS

C-2.1 The formulae given in **C-1** for two-winding transformers can be applied to three-winding transformers, and their regulation calculated with an accuracy comparable to that of the data available, by assuming that the currents in the windings remain constant both in magnitude and phase angle even through the output terminal voltages change, due to the regulation, from their no-load values.

On a three winding transformer the no-load voltage of a winding will change with current in the other windings (even though it remains itself unloaded).

Therefore, the voltages regulation of a winding on a three-winding transformer is expressed with reference to its no-load open-circuit terminal voltage when only one of the other windings is supplied and the third winding is on no-load, that is the basic voltage for each winding and any combination of loading is the line no-load voltage obtained from its turns ratio.

For the frequent case of two output windings (W_2 and W_3) and one input winding (W_1) the voltage regulation is usually required for three loading conditions, namely :

Only W_2 loaded,
Only W_3 loaded, and
Both W_2 and W_3 loaded.

For each condition two separate figures should be quoted, that is the regulation of each output winding W_2 and W_3 (whether carrying current or not) for constant voltage supplied to the winding W_1.

NOTE—The regulation between W_2 and W_3 relative to each other for this simple and frequent case is simplicit in the values (W_1 to W_2) and (W_1 to W_3) and nothing is gained by expressing it separately.

C-2.2 The data required are the impedance voltage and load losses derived by testing the three windings in pairs and expressing the results on a basic kVA, which can conveniently be the rated kVA of the smallest winding. It should be determined from the transformer as built.

From the data, an equivalent circuit is derived as shown in Fig. 4.

C-2.3 The equivalent circuit is derived as follows :

Let

a_{12} and b_{12} be respectively the percentage resistance and reactance voltage referred to the base kVA and contained on a test, short-circuiting either winding W_1 and W_2 and supplying the other, with the third winding W_3 on open circuit;

a_{23} and b_{23} similarly apply to a test on the winding pair W_2 and W_3 (with W_1 on open circuit);

a_{31} and b_{31} similarly apply to a test on the pair of windings W_3 and W_1 (with W_2 on open circuit);

$d=$ the sum $(a_{12}+a_{23}+a_{31})$; and

$f=$ the sum $(b_{12}+b_{23}+b_{31})$.

Then the mathematical values to be inserted in the equivalent circuit are :

Arm W_1 $a_1 = d/2 - a_{23}$, and $b_1 = f/2 - b_{23}$
Arm W_2 $a_2 = d/2 - a_{31}$, and $b_2 = f/2 - b_{31}$
Arm W_3 $a_3 = d/2 - a_{12}$, and $b_3 = f/2 - b_{12}$

It is to be noted that some of these mathematical values may be negative or may even be zero (depending on the actual physical relative arrangement of the windings on the core).

For the desired loading conditions the kVA operative in each arm of the equivalent circuit is determined and the regulation of each arm is calculated separately. The regulation with respect to the terminals of any pair of windings is the algebraic sum of the regulations of the corresponding two arms of the equivalent circuit.

C-2.4 The detailed procedure to be followed in the case of two output windings and one supply winding is as follows :

a) Determine the kVA in each winding corresponding to the loading being considered.

b) For the output windings W_2 and W_3, this is the specified loading under consideration; deduce n_2 and n_3, where n is the ratio of the actual loading to the base kVA used in the equivalent circuit.

c) For the input winding W_1, kVA should be taken as the vectorial sum of the outputs from W_2 and W_3 windings, and the corresponding power factor and quadrature factor (sin ϕ) deduced from the in-phase and quadrature components.

C-2.5 When greater accuracy is required, an addition should be made to the above vectorial sum of the outputs as follows :

Add to the quadrature component, to obtain the effective input kVA to winding W_1;

$$\text{(output kVA from winding } W_2) \times \frac{b_2}{100} \times n_2 +$$

$$\text{(output kVA from winding } W_3) \; \frac{W \times b_3}{100} \times n$$

n for each arm being the ratio of the magnitude of the actual kVA loading of the winding to the base kVA employed in determining the network.

A more accurate solution is obtained by adding the corresponding quantities ($a \times n \times$ output kVA) to the in-phase component of the vectorial sums of the outputs, but the difference is rarely appreciable.

C-2.6 Apply the final formula of **C-1.5** separately to each arm of the network, taking separate values of *n* for each arm as defined in **C-2.5**.

C-2.7 To obtain the regulation between the input winding and either of the loading windings, add the separate regulations determined under **C-2.6** for the corresponding two arms, noting that one of these may be negative. (Note that the summation is algebraic, and not vectorial).

NOTE — A positive value for the sum determined indicates a voltage drop from no-load to the loading considered, while a negative value for the sum indicates a voltage rise.

C-2.8 Repeat the operation described in **C-2.7** for the other loaded winding.

C-2.8.1 The above procedure is applicable to auto-transformers if the equivalent circuit is based on the effective impedances measured at the terminals of the auto-transformer.

C-2.8.2 In the case of input to two windings and load from one winding, the above procedure can be applied if the division of loading between the two supplies is known.

C-2.8.3 *Example of Application to a Three-Winding Transformer* :

Assume that :

W_1 is a 66 kV primary winding,

W_2 is a 33 kV output winding loaded at 2 000 kVA having a power factor cos ϕ of 0·8 lagging, and

W_3 is a 11 kV output winding loaded at 1 000 kVA having a power factor cos ϕ of 0·6 lagging.

The following information is available, having been calculated from test data and is related to a base kVA of 1 000 :

$a_{12} = 0{\cdot}26$ $\quad b_{12} = 3{\cdot}12$

$a_{23} = 0{\cdot}33$ $\quad b_{23} = 1{\cdot}59$

$a_{31} = 0{\cdot}32$ $\quad b_{31} = 5{\cdot}08$

It can be deduced that

$d = 0{\cdot}91$, and $f = 9{\cdot}79$

It follows, therefore, that for

arm W_1, $a_1 = 0{\cdot}125$ and $b_1 = +\ 3{\cdot}305$

arm W_2, $a_2 = 0{\cdot}135$ and $b_2 = -\ 0{\cdot}185$

arm W_3, $a_3 = 0{\cdot}195$ and $b_3 = +\ 1{\cdot}775$

The effective full load input kVA to winding W_1 is :

a) With only output winding W_2 loaded = 2 000 kVA at power factor 0·8 lagging

b) With only output winding W_3 loaded = 1 000 kVA at power factor 0·6 lagging

c) With both output windings W_2 and W_3 loaded = 2 980 kVA at power factor 0·74 lagging.

Applying the formula of **C-1.5** separately to each arm of the network we have for the regulation of that arms alone.

W_1 under condition (a) where $n_1 = 2{\cdot}0$ is + 4·30 percent
W_1 under condition (b) where $n_1 = 1{\cdot}0$ is + 2·74 percent
W_1 under condition (c) where $n_1 = 2{\cdot}98$ is + 7·15 percent
W_2 where $n_2 = 2{\cdot}0$ is — 0·005 percent
W_3 where $n_3 = 1{\cdot}0$ is + 1·54 percent

Therefore the total transformer regulation is :

For condition (a) — With output winding W_2 fully loaded and W_3 unloaded.

At terminals $W_2 = 4{\cdot}30 - 0{\cdot}005 = 4{\cdot}295$ percent
At terminals $W_3 = 4{\cdot}30 + 0 = 4{\cdot}30$ percent.

For condition (b)—With output winding W_2 unloaded aad W_3 fully loaded :

At terminals $W_2 = 2{\cdot}74 + 0 = 2{\cdot}74$ percent
At terminals $W_3 = 2{\cdot}74 + 1{\cdot}54 = 4{\cdot}28$ percent

For condition (c)—With both output windings W_2 and W_3 loaded :

At terminals $W_2 = 7{\cdot}15 - 0{\cdot}005 = 7{\cdot}145$ percent
At terminals $W_3 = 7{\cdot}15 + 1{\cdot}54 = 8{\cdot}69$ percent.

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